Why Aharonov-Bohm Effect Does Not Violate Locality Principle

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Abstract: *Two hypotheses concerning the Lagrange function postulating for a system with electromagnetic interactions: "vortex" (classic) and "gradient" (new) are compared. It is shown that the gradient hypothesis, unlike the vortex one, does not result in conflict between the Aharonov-Bohm (AB) effect and the locality principle. A modification of AB effect in Zero Magnetic (ZM) oscillation of potential around excited closed waveguide is predicted.*

Keywords: Aharonov-Bohm effect; locality principle; electromagnetic potential; Lagrange function.

Introduction

Convergence of vacuum and solid-state electronics to a fundamentally new nanotecnological form is very probable. Quantum mechanics and quantum electrodynamics set a physical base of nanotechnology, like classic mechanics and electrodynamics are basis for the "old" engineering.

However, long-standing problems like Aharonov-Bohm (AB) effect [1] physical interpretation may complicate the abovementioned process. As numerous publications reveal, there is no way to reconcile this effect with the locality principle using the field formalism. Let's consider what the self-sufficient potential formalism [2, 3] proposes instead.

The Lagrange function volume density for a system with electromagnetic (EM) interactions consists of three terms: $\lambda(t,x,y,z)=\lambda^P+\lambda^I+\lambda^S$ [2–4]. λ^P is a "mechanical" term for particles. $\lambda^I=-\vec{A}\cdot\vec{j}$ is an interaction term between the particles and EM field (in field formalism) or Minkowski space-time considered as a distributed EM oscillating system (in potential formalism). λ^S describes field itself or the oscillating system itself respectively; this may be postulated using two different hypotheses: vortex

$$\lambda^S=-\frac{1}{2\mu_0}(\vec{\nabla}\times\vec{A})^2$$

and gradient

$$\lambda^S=-\frac{1}{2\mu_0}\left[(\vec{\nabla}A_t)^2-(\vec{\nabla}A_x)^2-(\vec{\nabla}A_y)^2-(\vec{\nabla}A_z)^2\right].$$

$\vec{j}(t,x,y,z)$ is the current density four-vector; $\vec{\nabla}\times\vec{A}$ is a tensor of the four-curl of the EM potential four-vector $\vec{A}(t,x,y,z)$ [5]; $\vec{\nabla}A_\tau$ is the four-gradient of A_τ; τ is a generic symbol for $t\equiv ct$, x, y, or z.

Main Part

The locality principle expresses itself in the energy-momentum flow continuity law. This flow is described by the energy-momentum tensor $\left[w\right]=\left[w^P\right]+\left[w^I\right]+\left[w^S\right]$.

"Mechanical" tensor for particles is described in [4]. Components of interaction tensor between the particles and EM field (or the oscillating system) are $w^I_{\tau\tau'}=A_\tau j_{\tau'}$. Components of the last tensor are calculated as [4]:

$$w^S_{\tau\tau'}=g_{\tau\tau}\sum_{\tau''}\frac{\partial A_{\tau''}}{\partial\tau}\frac{\partial\lambda^S}{\partial(\partial A_{\tau''}/\partial\tau')}-g_{\tau\tau'}\lambda^S ,$$

where $\left[g\right]$ is the diagonal metric tensor for the pseudo Euclidian space. As known, $\left[w^S\right]$ is originally asymmetric in the vortex hypothesis. Therefore, special symmetrization procedure must be applied to one to guarantee the angular momentum conservation. Such procedure is described in [4] for a specific case $\vec{j}\equiv 0$, but described in [5] general case of $\vec{j}\neq 0$ is of particular interest. It is shown that $\left[w^I\right]$ vanishes from $\left[w\right]$ after the symmetrization. The symmetrization displaces EM energy and momentum of a closed system by "taking away" those from charged particles and "spreading" over the space where $\vec{\nabla}\times\vec{A}$ tensor is non-zero. "Non-physical" relocation of energy-momentum is the prime cause of some EM paradoxes like a seeming violation of locality principle in AB effect.

For the gradient hypothesis, $\left[w^S\right]$ is symmetric natively:

$$w^S_{\tau\tau'}=-\frac{g_{\tau\tau}g_{\tau'\tau'}}{\mu_0}\left(\frac{\partial A_t}{\partial\tau}\frac{\partial A_t}{\partial\tau'}-\frac{\partial A_x}{\partial\tau}\frac{\partial A_x}{\partial\tau'}-\frac{\partial A_y}{\partial\tau}\frac{\partial A_y}{\partial\tau'}-\frac{\partial A_z}{\partial\tau}\frac{\partial A_z}{\partial\tau'}\right)+$$
$$+\frac{g_{\tau\tau'}}{2\mu_0}\left[(\vec{\nabla}A_t)^2-(\vec{\nabla}A_x)^2-(\vec{\nabla}A_y)^2-(\vec{\nabla}A_z)^2\right]. \qquad (1)$$

Note that EM energy and momentum are transferred by A_t, A_x, A_y, A_z components independently in the gradient hypothesis, like a perfectly elastic body.

Let's consider a perfectly conductive empty spherical cavity centered at $(t,0,0,0)$ that carries linearly increasing in time voltage $U(t)=\dot{U}_0 t$. Solution of the D'Alembert equation for $\vec{A}(t,r)$ inside the cavity is as $A_t=(\dot{U}_0/c)t$; $A_r=-(\dot{U}_0/3c)r$, where $r^2=x^2+y^2+z^2$.

If a rest particle with charge q is placed at (t,0,0,0), the potential inside becomes superposition of both potentials: $A_t = (\dot{U}_0 / c)t + (\mu_0 cq / 4\pi)r^{-1}$; A_r is unchanged.

Let's enclose the particle with an imaginary spherical surface of radius r. According to (1), the surface density of EM energy radial flow outwards this surface is

$$w_{tr}^S(t,r) = \frac{c}{\mu_0}\frac{\partial A_t}{\partial t}\frac{\partial A_t}{\partial r} = -\frac{q}{4\pi}\dot{U}_0 r^{-2} . \qquad (2)$$

Integrating (2) over the surface $4\pi r^2$, note that growth of EM energy within the surface for a time dt: $dW = q\dot{U}_0 dt$ is the same as increase of the interaction energy $dW^I = cqdA_t$ because energy of the EM oscillating system W^S inside the surface and the particle mechanical energy W^P are unchanging. Just W^I, not W^S, provides the wavefunction phase incursion along a closed 4D loop L :

$$\Delta\varphi = \frac{q}{\hbar}\oint_L \vec{A}(t,x,y,z)\cdot d\vec{l} .$$

Thus, there is no contradiction between the AB effect and the locality principle in the gradient hypothesis if the wavefunction phase depends on A_t. Components $w_{t\xi}^S$ ($w_{\xi t}^S$) are non-zero inside the conductive cavity while its voltage varies in time (ξ is a generic symbol for x, y, or z). EM energy flows to the charged particle (or spreads from one). A similar situation has a place when the wavefunction phase depends on A_ξ. While a charged particle approaches to a long solenoid, components $w_{\xi\xi'}^S$ are non-zero outside in the gradient hypothesis, so EM momentum flows to the particle. Such case is harder, so not considered here.

The gradient hypothesis predicts one more kind of the AB effect when an electron wavepacket flows around a waveguide with EM wave. The BCs for $\vec{A}$ components on conductive or totally reflective surfaces differ from the BCs for EM field components. Therefore, $\vec{A}$ components are non-zero around an excited resonator or waveguide. The excited resonators (waveguides) are surrounded by the *Zero Magnetic* (*ZM*) oscillations of potential [6]. *ZM* oscillations can influence the phase of the electron wavepacket.

An experiment can be made as in Fig. 1. The electron wavepacket W that has bypassed two slots 1 and 2 flows around a thin single-mode optical fiber *OF* and interferes on the screen S behind. If there is no light in the fiber, the interference figure looks as fringes I_1. When light is transmitted over the fiber, currents and charges on the bound of this waveguide excite a RF potential around it. This produces RF modulation of the wavepacket phase causing diffusion of the interference pattern (I_2). The effect is weak because the phase shift is averaged over many RF periods, but enlarges as the wavepacket group velocity increases. To ensure reliable shielding, the fiber may be covered with a layer of superconductor. Energy-momentum flow to the electron wavepacket also exists in this kind of AB effect, but its averaged per cycle value is almost zero.

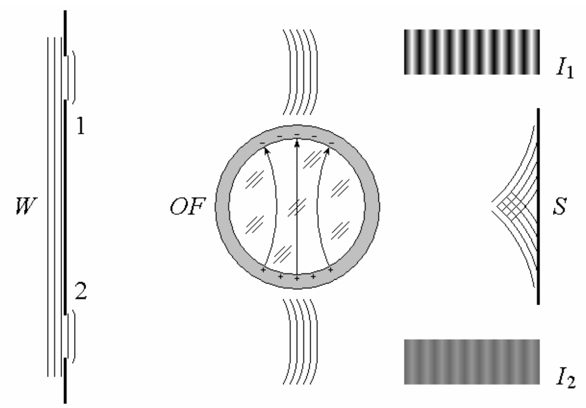

Figure 1

Conclusion

The AB effect has simple and "elegant" interpretation in the self-sufficient potential formalism using the gradient hypothesis. No conflict with the locality principle appears. Moreover, a new modification of AB effect is predicted around excited resonators and waveguides.

References

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